Improving Current Transformer-based Energy Extraction from AC Power Lines by Manipulating Magnetic Field

Y. Zhuang, C. Xu, C. Song, A. Chen, W. Lee Y. Huang, *Senior Member*, *IEEE*, and J. Zhou

***Abstract*— This paper presents a novel method to improve energy scavenging from AC power lines under magnetic saturation conditions. The extracted power level of a conventional magnetic energy harvester is limited by the maximum flux density of the magnetic core. When a magnetic core is clamped on AC power lines, the flux density in the core is proportional to the magnetic field strength around the power line. Choosing a high-permeability core has the advantage of harvesting more energy for a given primary current. The flux density in such a core could reach its maximum value when the magnetic field increases. In this scenario, very little energy can be harvested since flux density variation in the core is small. Here we introduce an artificial magnetic field by adding an additional control coil to manipulate the magnetic field of power lines. A power management circuit is employed to store the energy harvested by the control coil and feed it back to the harvester to generate a counter magnetic field. As a result, the core will not be easily driven into the saturation region; hence more energy can be harvested. Experimental results show that the proposed energy harvester can harvest an average power of 283 mW on a 50 Hz 10 A_{rms} power line (2.34 mW/cm^3/A_{rms}), which is increased by 45% compared with the device without the control coil. This new method could provide a promising solution for smart grid monitoring and other industrial sensing applications.**

***Index Terms*— AC power line, electromagnetic energy harvester, energy harvesting, magnetic saturation.**

I. Introduction

FOR smart grid applications, the real-time monitoring of device features and environmental parameters such as current, voltage, humidity and temperature of power infrastructures is very important. Wireless sensors can be used to monitor and report the status of power lines. They are affordable, and their power consumption is relatively low. Energy harvesting (EH) technique is one of the most promising solutions for powering self-sustainable wireless sensing devices. They have been widely demanded by the industry such as in smart grid applications [1]-[3]. EH devices have been extensively researched for many different energy sources in the ambient environment such as oceanic wave [4], solar [5], [6], wind [7], [8], vibration [9] and kinetic [10]. However, solar and wind energy harvesters usually rely on the weather condition and require energy storage devices for night or low wind operations, respectively [11]. Based on the UK National Grid data [12], a typical substation has an average electric field strength of 10 kV/m and a magnetic field of 32 A/m, which can be a consistent and reliable energy source to drive sensors.

Electromagnetic energy harvesting techniques and topologies have been widely studied to harvest environmental energy [13]- [24]. However, almost all electric field harvesters are limited by the reactance of the coupling capacitor which only has a capacitance up to tens of pF and a relatively large size (a tube with a diameter of 30 cm and a length of 55 cm in [13]). Thus, inductors with MH (Mega Henry) inductance are required to realize resonance at the power line frequency of 50/60 Hz. Such inductors are very difficult to implement. The magnetic field harvesters are important candidates due to the relatively small toroid core can be used to reduce the circuit size. Also, the inductance of a toroid coil is typically in the range of mH to H, and the corresponding capacitor should be in the range of nF to mF to resonate at 50/60 Hz, which are commercially widely available. A magnetic field energy harvester can collect a relatively large amount of energy even with a low primary side current [14], [15]. However, magnetic saturation will occur if the primary current is excessive, which will cause voltage distortion and high-order harmonics [16]. Power loss in a magnetic energy harvester due to magnetic saturation was analysed in [17]-[19]. A method to improve the harvesting efficiency under the magnetic saturation condition was reported in [18] by using a transfer window. [20] employed a dissipative resistor and an over-voltage protection unit to avoid saturation. However, the self-dissipation of the resistor is significantly increased. Two toggled secondary coils are used to prevent saturation with high current to increase the harvested power, but the implementation of two cores will make the system bulky [21]. The smart stick-on sensors suggested in [22] can operate over a wide range of source currents from 60 A to 1000 A with the advantages of low cost and easy installation. The magnetic saturation problem was mitigated by using stick-on devices, but the harvested power was limited. Also,

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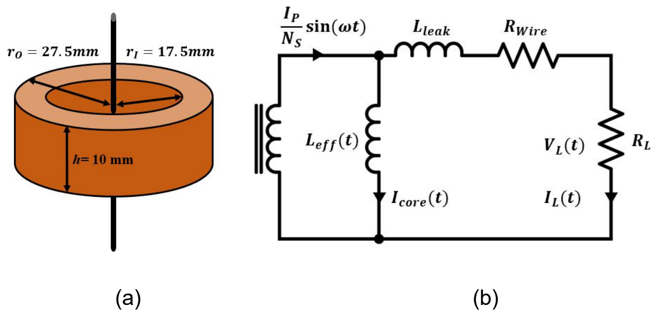

Fig. 1. (a) Magnetic core structure, (b) equivalent circuit of the current transformer-based energy harvesting circuit.

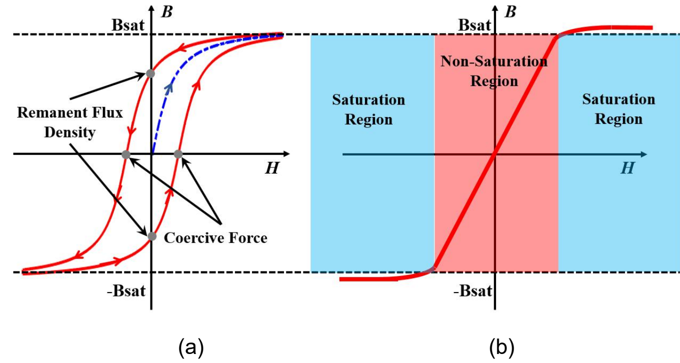

Fig. 2. (a) A typical B-H curve of the core, (b) an idealized B-H curve.

[23] and [24] used an optimized core shape to increase the harvested power without saturation. However, the power level is relatively low. As analysed in [18], the magnetic saturation is the main limitation on the harvested power level. Hence, by avoiding the magnetic saturation condition, the harvested power can be significantly improved.

This paper presents a novel method for an electromagnetic EH to maximize the energy extraction from AC power lines under magnetic saturation conditions. The proposed method employs a core that is clamped on a power line. The core usually has a high permeability so that it can harvest sufficient power even when the current on the power line is low. Owing to the high magnitude of current flow on the power line, this core can be easily driven to its magnetically saturated region. An artificial magnetic field is introduced to manipulate the magnetic field induced by the power line, so that the core is mainly working in the unsaturated region. With the aid of the presented novel method, the harvested power is significantly increased. The paper is organized as follows: Section II discusses current transformer based EH devices and a circuit model will be built to analyze challenges of energy harvesting under the magnetic saturation condition. Section III gives details of the proposed method and numerical simulation results of the proposed prototype. Then, the measured results and experimental validation are shown in Section IV. Section V concludes the paper.

II. Energy Extraction from AC Power Line

A. Circuit Modelling and Idealization

Fig. 1(a) shows a magnetic core model as well as the dimensions of the core used in this work, where r_I, r_O and h are the inner radius, outer radius and the height of the core, respectively. The magnetic flux path length and the cross-section area of the core are l_{eff} and A_{core}. Fig. 1(b) shows an equivalent circuit of the magnetic core as a secondary circuit [18]. The number of turns of the coil winding, the primary side sinusoidal current, the magnetizing inductance, the magnetizing current, the leakage inductance, the load current, the coil resistance and load resistance are N_S, $I_P sin(\omega t)$, L_{eff}, $I_{CORE}(t)$, L_{Leak}, $I_L(t)$, R_{Wire} and R_L. Because the core used in this work has a very high permeability, the leakage inductance is negligible compared with the magnetizing inductance. It is assumed that the wire used in the analysis is lossless, hence R_{Wire} = 0. Then, the power harvested on the load can be expressed as:

$$P_{Load} = \frac{1}{2} I_p^2 \frac{R_{Load}}{N_S^2} \tag{1}$$

The harvested power level on the load depends on the primary side current, load resistance and winding number of the coil. Eq. (1) is accurate under the condition that the core is not saturated when the magnetic flux density $B(t)$ is proportional to the magnetic field strength $H(t)$ induced by the primary current. A typical B-H curve of a magnetic core with the saturation behavior is shown in Fig. 2(a). There are two boundaries which limit the maximum positive and negative magnetic flux density in the core regardless of the magnetic field strength. The boundary of the magnetic flux density B_{sat} is determined by the properties of the material [25].

For a core clamped on a power line, when the conducting current is zero, each crystal in the core has a magnetic domain randomly oriented initially. When the current in the power line increases, a magnetic field is applied to the material which will re-orient some of the magnetic domains in the opposite direction of the external field. A stronger H will align more domains. The core now is in the non-saturation region, and the magnetic flux density is proportional to the power line current. A large amount of energy can be extracted from this region. When the current in the power line keeps increasing, almost all the domains will be aligned with the external H. The magnetic flux density will almost be kept constant at B_{sat}. The ferromagnetic material is said to be saturated when the magnetic flux density reaches B_{sat}. In the saturation region, there is little flux change in the core even if the magnitude of the current is getting much higher.

In the proposed design, the main limitation of the harvested power level is the magnetic saturation. The nonlinear B-H behavior can be idealized using the arctangent function proposed in [17]:

$$B(t) = B_{sat} \frac{2}{\pi} \arctan\left(\beta H(t)\right) \tag{2}$$

where the constant β represents the sensitivity of the core in the non-saturation region [17]. $B_{sat} \cdot 2/\pi$ is used to de-normalize the function to the maximum flux density B_{sat} when the core is saturated. The idealized B-H curve can be divided into the

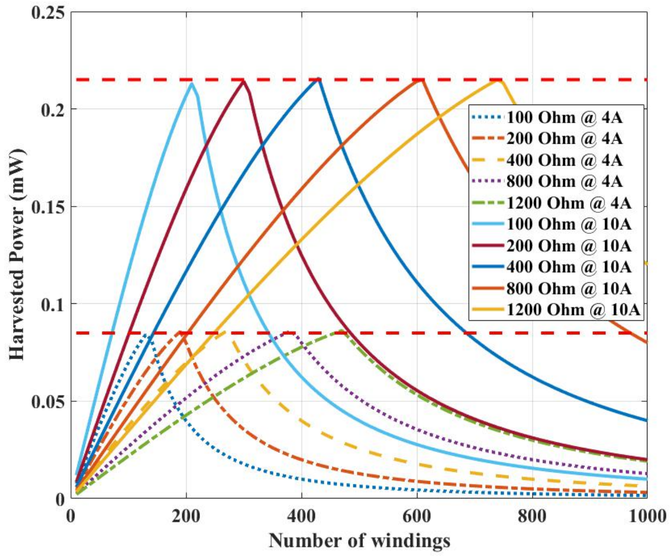

Fig. 3. Simulated harvested power against the winding number with different load resistances at 4 A_{rms} and 10 A_{rms} primary currents.

saturation and the non-saturation region as shown in Fig. 2(b). Theoretically, the flux density will keep increasing even when B_{sat} is achieved in the core due to that the permeability of vacuum (free space) will still introduce a very small flux change. However, the vacuum flux variation is very small and can be ignored in the analysis [26]. The core is saturated once the core magnetic flux density reaches B_{sat}.

B. Power Analysis

The load voltage V_L that induced by the flux density variation can be calculated as:

$$V_L(t) = \frac{I_P R_L}{N_S}\sin(\omega t) = N_S A_{core}\frac{dB(t)}{dt} \tag{3}$$

If the core used in the EH system is driven into the saturation region, the time point that the core starts to saturate can be denoted by t_{sat}. At t_{sat} the flux density will reach its maximum value B_{sat}, then, (3) can be expressed as:

$$A_{core} N_S B\left(t_{sat}\right) = \int_0^{t_{sat}} \frac{I_P R_L}{N_S}\sin\left(\omega t\right)dt \tag{4}$$

The time point t_{sat} can be solved as:

$$t_{sat} = \frac{1}{\omega} arccos\left(1 - \frac{\omega B_{sat} A_{\text{core}} N_S^2}{R_L I_P}\right) \tag{5}$$

The saturation time depends on not only the core material and the primary current, but also the secondary circuit. The parameters of the secondary circuit can be combined into one, namely, a load index k:

$$k = \frac{N_S^2}{R_L} \tag{6}$$

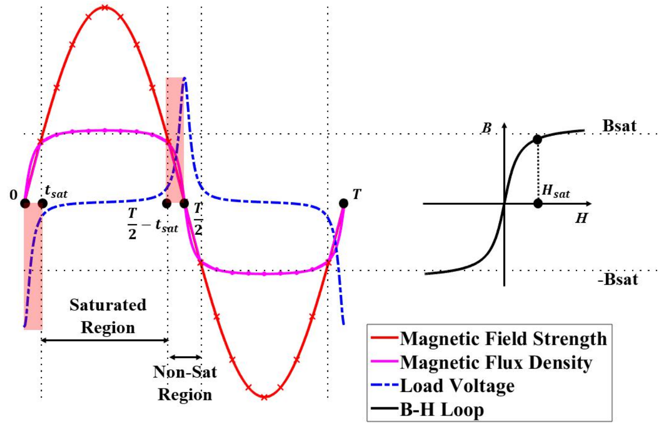

Fig. 4. Simulated waveforms and the B-H loop of the core.

The harvested power on the load during the non-saturation region P_{non} for a quarter period of the primary current can be calculated as:

$$\begin{aligned} P_{\text{non}} &= \frac{4}{T}\times\int_0^{t_{sat}} R_L\left(\frac{I_p}{N_S}\sin(\omega t)\right)^2 dt \\ &= \frac{4I_P^2}{Tk}\int_0^{t_{sat}} \sin^2(\omega t)dt \\ &= \frac{4I_P^2}{Tk}\left(\frac{t_{sat}}{2} - \frac{\sin(2\omega t_{sat})}{4\omega}\right) \end{aligned} \tag{7}$$

The relationship of the harvested power against the winding number with different load resistances at 4 A_{rms} and 10 A_{rms} primary current is illustrated as Fig. 3. (f = 50 Hz, A_{core} = 1 cm^2 and B_{sat} = 1.2 T). The maximum harvested power for a given core can be achieved by tuning the load resistance for different winding numbers. The maximum power is only determined by the primary current and the properties of the core. For each primary current magnitude, there exists one optimal load index k_{opt} leading to the maximum harvested power. If the primary current is strong enough to saturate the core, changing the number of turns will only change the optimal value of the load resistance. It will have little effect on the value of the maximum power.

The relationship among the load voltage, magnetic field strength and magnetic flux density in the core and the B-H curve is plotted as shown in Fig. 4. The voltage across the load is non-zero for a small period when the core is not saturated. The magnetizing inductance can be treated as a parallel source impedance of an ideal current source as shown in Fig. 1(b). When the core is not saturated, the source impedance is very high and the current $I_{CORE}(t)$ flows into it will be near-zero, therefore almost all the current is consumed by the load. When the core is saturated, the increase of the magnetic flux density is negligible when the primary current keeps increasing. The source impedance will be very low, like a short circuit, letting $I_{CORE}(t)$ flow through it to set up the magnetic flux [17]. The maximum harvested power will be achieved with a non-zero flux density change in the core. In this case, the flux density in the core should decrease when its value reaches B_{sat}. The k_{opt} can

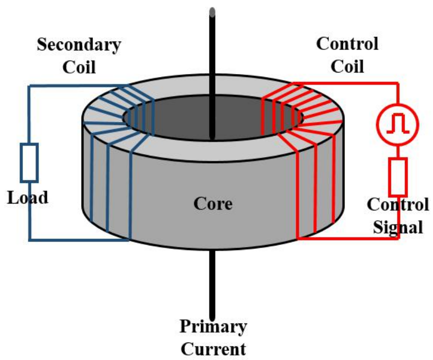

Fig. 5. The Proposed energy harvesting structure by adding a contro coil to apply control current.

be calculated by setting t_{sat} = T/4 as:

$$t_{sat} = \frac{T}{4} = \frac{1}{\omega} arc\cos(1 - \frac{\omega B_{sat} A_{\mathrm{core}} k_{opt}}{I_P}) \tag{8}$$

$$k_{opt} = \frac{I_P}{\omega B_{sat} A_{core}} \tag{9}$$

Now, the maximum harvested power can be calculated by substituting (9) into (1):

$$P_{\max} = \frac{\omega I_P B_{sat} A_{core}}{2} \tag{10}$$

The above analysis suggests that to harvest energy from AC power lines with more power, a core with a higher saturation magnetic flux density is desired. Based on Santos *et al.'s* [25] research, nano-crystalline is selected as the magnetic core in this work.

III. Proposed Energy Harvesting Method

A. Magnetic Field Manipulation

Conventional methods of harvesting maximum power aim to desaturate the core by using more windings, reducing the load resistance or using larger core as can be derived from (4). As shown in Fig. 4, the magnetic flux density will not increase significantly when it reaches B_{sat} regardless of the increase of the magnetic field strength. From energy harvesting point of view, it is not very effective since the variation of the magnetic field strength will cause very little change of the flux density. As a result, making full use of the magnetic field strength variation in the saturation region can further increase the harvested power.

As discussed in Section II, the core of a magnetic field energy harvester can be easily saturated by the strong current in the power line. More energy could be harvested by de-saturating the core. This can be realized by applying a current with a direction opposite to that of the primary side. A controlled magnetic field H_C can be applied to the core artificially to manipulate the resultant magnetomotive force. It can prevent the core from being saturated.

To introduce the artificial magnetic field to the core, a control current winding is needed as aforementioned. The proposed energy harvester structure is illustrated in Fig. 5. The control coil has a winding number of N_C, which conducts a DC current with a magnitude of I_C in the opposite direction of the power line current. The current will only be applied when the core is nearly saturated. In this case, based on the vector superposition, the equivalent magnetizing field strength in the core can be expressed as:

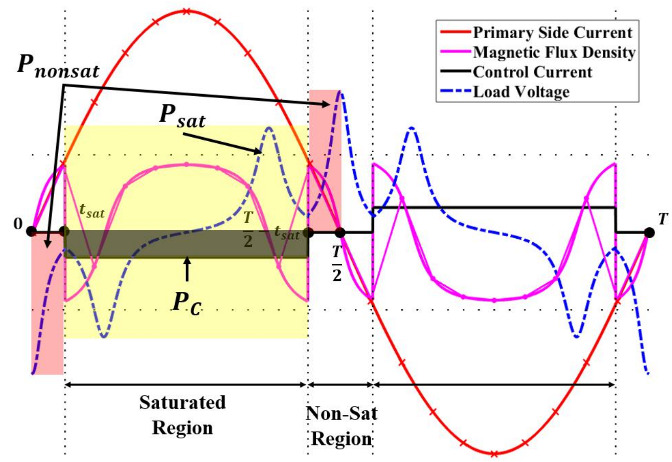

Fig. 6. Simulated waveforms on the core with the proposed method.

$$H_{eff}(t) = \frac{I_P \sin(\omega t) - I_C}{l_{eff}} \tag{11}$$

In order to ensure the core will not be saturated during the whole period of the primary current, the magnitude of the control current should be able to pull the effect of I_P back to a level that it will not saturate the core. On the other hand, the applied control current will consume energy. Hence to harvest energy efficiently, the control current should be as small as possible, just about sufficient to desaturate the core. The magnitude of the control current can be calculated by:

$$I_C = I_P - I_P \sin(\omega t_{sat}) = I_P \left(1 - \sqrt{1 - \left(1 - \frac{\omega B_{sat} A_{eff} k}{I_P}\right)^2}\right) \tag{12}$$

The control current should only be applied when the core is about to work in the saturation region. Therefore, the applying time duration t_C for each quarter of the primary current period should be equal to the saturation time:

$$t_C = \frac{T}{4} - t_{sat} = \frac{T}{4} - \frac{1}{\omega} ar\cos(1 - \frac{\omega B_{sat} A_{\mathrm{core}} k}{I_P}) \tag{13}$$

The waveforms of the primary side current, magnetic flux density, load voltage and added control current on the circuit are illustrated in Fig. 6. Contributed by the control current, the magnetic flux density will not reach B_{sat}. There will be a flux density variation in the core most of the time in a period. Therefore, the amount of harvested energy on the load can be increased significantly.

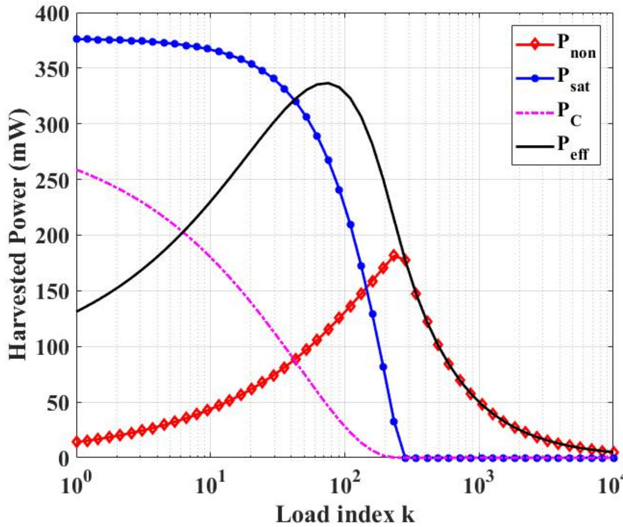

Fig. 7. Calculated P_{nonsat}, P_{sat}, P_C and P_{eff} against load index k.

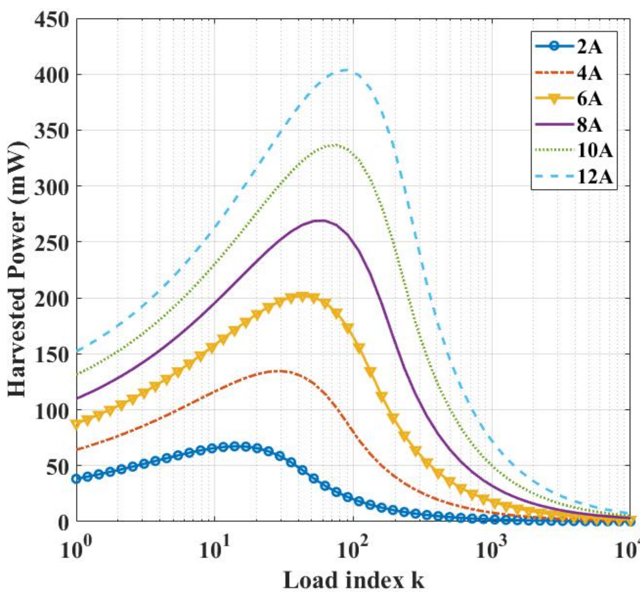

Fig. 8. Calculated P_{eff} against k with different primary currents.

B. Power Analysis and Numerical Calculations

Compared with the conventional method with waveforms shown in Fig. 4, the energy harvesting circuit with the proposed method can harvest energy during not only the non-saturation region but also the normally saturated region as shown in Fig. 6. The power harvested in the saturation region P_{sat} for a quarter period with the control current can be calculated as:

$$\begin{aligned} P_{sat} &= \frac{4}{T}\int_{t_{sat}}^{(\frac{T}{4})}\left(\frac{(I_P\sin(\omega t)-I_C)}{N_S}\right)^2 R_L dt \\ &= \frac{4I_P^2}{Tk}\left(\frac{t_{sat}}{2}-\frac{\sin(2\omega t_{sat})}{4\omega}\right) \\ &\quad -\frac{4I_PI_C}{\pi k}\cos(\omega t_{sat})+\frac{4I_C^2}{Tk}\left(\frac{T}{4}-t_{sat}\right) \end{aligned} \tag{14}$$

However, it does consume energy to apply the control current. The control current I_C is provided by a constant voltage source

TABLE I
CORE PARAMETERS AND CIRCUIT SETUP

Core material:	Nanocrystalline, Fullstar No. 312
Number of secondary winding	$N_S = 100$
Number of control winding	$N_C = 100$
Winding resistance	$R_W = 0.86\ \Omega$
Core height (with/without case):	$H = 10/9.5$ mm
Outer radius (with/without case):	$r_o = 27.5/27$ mm
Inner radius (with/without case):	$r_i = 17.5/18$ mm
Maximum flux density:	1.19 T
AC line current:	10 A_{rms}
Frequency:	50 Hz
Load resistor:	$R_L = 67\ \Omega$
Power management unit:	MAX17710
Micro-controller unit:	LAUNCHXL-F28377S BOOSTXL-DRV8305

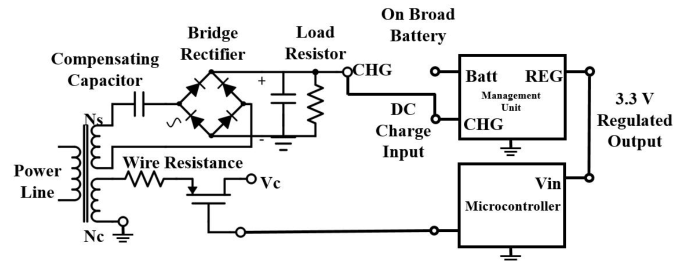

Fig. 9. A schematic circuit of the proposed energy harvester.

V_C on N_C number of windings on the core. The power consumed by the control current for each quarter period can be calculated by:

$$P_C = \frac{4}{T}\frac{I_C}{N_C}V_C\left(\frac{T}{4}-t_{sat}\right) \tag{15}$$

Hence, the effective power harvested on the load P_{eff} can be calculated by:

$$P_{eff} = P_{nonsat} + P_{sat} - P_C \tag{16}$$

For a given I_P, the parameters t_{sat}, P_{nonsat}, P_{sat} and P_C are all dependent on the value of k. A numerical calculation of the response of P_{nonsat}, P_{sat} and P_C against k with $I_P = 10$ A_{rms} and $N_C = 100$ is carried out as shown in Fig.7. P_{eff} is calculated against k with different primary currents as shown in Fig. 8. The core is not saturated with a large k. However, it does not mean the harvested power is high as can be seen in Fig. 8. As k decreases from a large value, more power can be harvested. But the core starts to be driven into the saturation region, preventing the power to increase further. Then, the control current is applied to keep the core working in the non-saturated region.

IV. MEASUREMENTS RESULTS

A. Power Consumption Analysis

Measurements on the energy harvester were carried out to validate the proposed method. The schematic circuit of the proposed energy harvester and the measurement setup are shown in Fig. 9 and Fig. 10. The core parameters and circuit components used in this system are listed in Table I.

In order to calculate the effective harvested power, all power consumptions of the units used in the system are considered. To generate the control current, a micro-controller unit

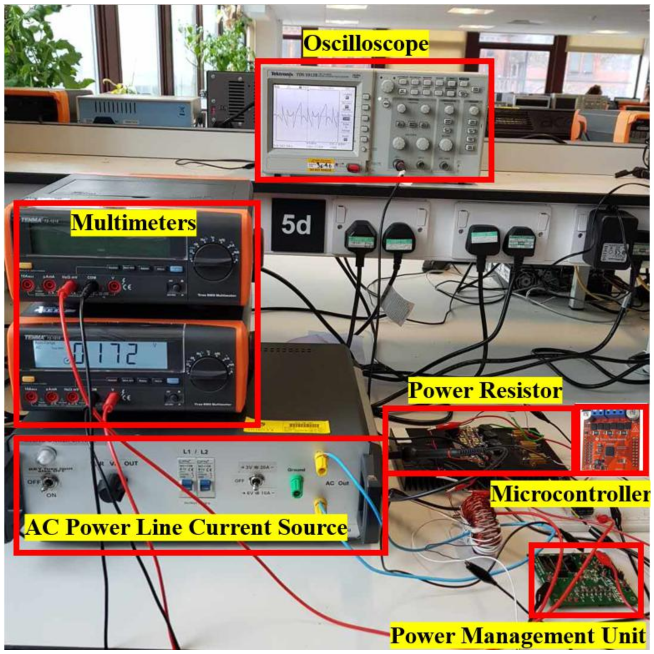

Fig. 10. A photograph of the measurement set-up.

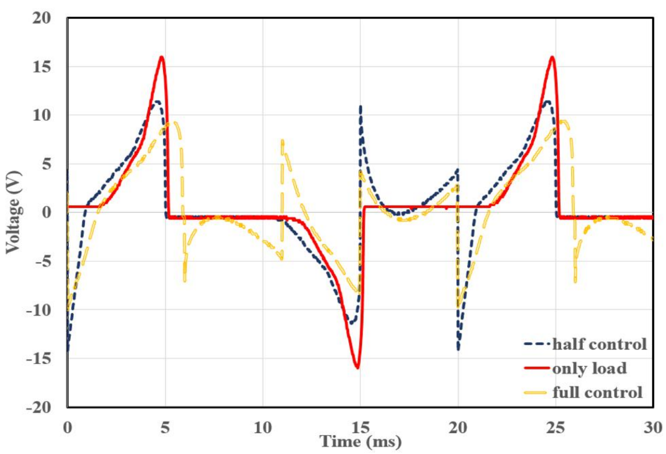

Fig. 11. Measured voltage waveforms on the coil with half cycle, full cycle control current and without control current.

LAUNCHXL-F28377S with a BOOSTXL-DRV8305 was used to control the period and direction of the current. The micro-controller contains CSD18540Q5A N-channel FETs with an ON-resistance of 1.8 mΩ. The unit consumes from several mW to tens of mW power depending on the ON/OFF ratio of the control current.

A power management unit MAX17710 was used to store the harvested energy from the secondary winding and feed a portion of the harvested power to provide the control current. The power management unit only consumes 150 µW (based on data sheet) which can be neglected in this work. There is an on-board battery in the management unit which is used to store the harvested energy. It can be replaced by an energy storing super-capacitor if necessary. The battery or super-capacitor can be charged by part of the harvested energy to make the harvester fully self-sustainable. The charging efficiency of a Li-ion battery can be well above 95% under optimal conditions [27].

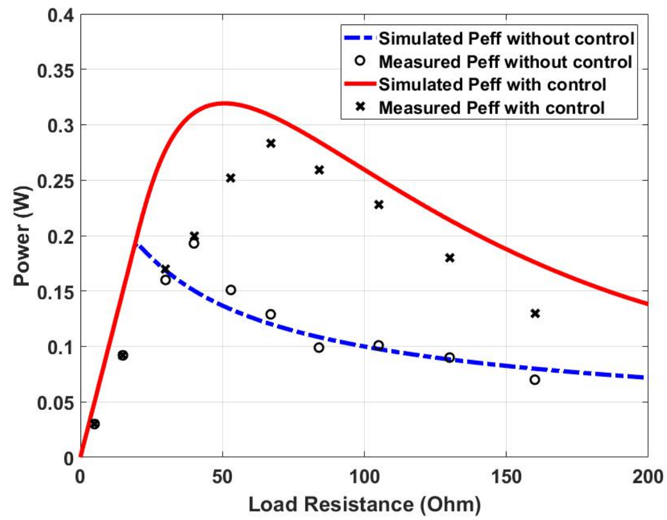

Fig. 12. Comparison of the simulated and measured output power of the circuit with and without the proposed method under 10 A primary current.

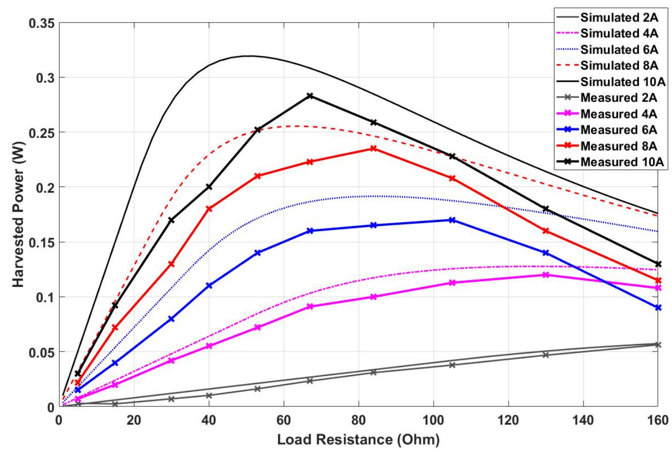

Fig. 13. Comparison of the simulated and measured results of the circuit with the proposed method under primary current varying from 2 A to 10 A against load resistance.

B. Measured Performance

A photo of the measurement setup is shown in Fig. 10. The core is clamped on a primary conductor. The conductor was connected to a current source to represent the AC power line. The secondary winding was connected to a series compensating capacitor for impedance matching purposes. Then, a bridge rectifier was connected to convert the harvested AC current into DC. A capacitor was placed after the rectifier in parallel with the load resistor to smooth the output voltage. The control winding was connected to a microcontroller which can switch ON or OFF the control current to compensate the magnetic field as required.

The waveforms of the energy harvester under a 10 A_{rms} primary current are measured by using an oscilloscope. The results are shown in Fig. 11. When the current on the control winding is not activated, the core is saturated for a large portion of a primary current period, which limits the power harvested from the power line. An average effective power of 193 mW can be harvested without using the proposed method. The control current was applied only when the core would have

TABLE II
CORE PARAMETERS AND CIRCUIT SETUP

Refs.	Core Volume (cm^3)	Harvested Power (mW)	Line Current (A_{rms} @ Hz)	Power Density ($mW/cm^3/A_{rms}$ @ Hz)
[18]	2.3	48.3	4 @ 60 Hz	5.2 @ 60 Hz
[28]	2.9	63.7	10 @ 50 Hz	2.0 @ 50 Hz
[29]	7.2	105	65.3 @ 50 Hz	0.2 @ 50 Hz
This work	12.1	283	10 @ 50 Hz	2.3 @ 50 Hz
This work with [18] core	2.3	40.2	4 @ 50 Hz	4.3 @ 50 Hz 5.2 @ 60 Hz

been working in the saturation region. When the current on the proposed control winding is only activated in the negative half-cycle, the average harvested power is increased to 230 mW. When the control current is fully activated in both half-cycles, the harvested power is significantly increased. The actual power on the load was 317 mW. The control current consumes 28 mW, and the microcontroller and power management unit consume 6 mW. The effective harvested power is therefore 283 mW. The corresponding power density in terms the volume of the core and the primary current is 2.34 $mW/cm^3/A_{rms}$, which is 46.3% higher than that without the control winding (1.6 $mW/cm^3/A_{rms}$).

Moreover, to validate that the proposed method can improve the harvested power for different cores, the experiment of the proposed method using the core from Vacuumschmelze [18] has also been performed. An effective power, as defined by (16), of 40.2 mW can be harvested from a 50 Hz, 4 A_{rms} primary current. The power density is effectively increased by 17.3 % with the suggested method. It shows that the proposed method is very competitive compared to existing technologies.

P_{eff} is dependent on k for a given primary current. Power harvested by the energy harvesting system under 10 A primary current was measured against the load value with a fixed number of winding $N_S = 100$. Fig. 12. shows the comparison of simulated and measured results with and without using the proposed method. The measured results are very close to the simulation in both cases. The measured power is slightly lower than the prediction which is mainly because of the unavoidable hysteresis loss and ohmic loss which are ignored in the calculation. Fig. 13. illustrates the comparison of simulated and measured results of the circuit with the proposed method under primary currents from 2 A to 10 A. The measured effective harvested power has good agreement with the simulated results, which verified the derived equations and the proposed method. It should be mentioned that when the primary current is increasing, the core will be driven into saturation region faster. Therefore, a longer duration and a higher level of control power is required to compensate for the excessive flux. It will lead to a higher control power consumption.

The proposed energy harvester can be designed on a clip-on core, which can be relatively easily installed on a transmission line. The energy harvesting system built in this paper is based on an MAX17710 and a Launchxl-F28377S evaluation board. For volume production, the cost of the device can be estimated by the main components of the system. The main parts used in the proposed controller are a power management chip (MAX17710GB+TCT-ND) £12.95 and a microcontroller (TMS320F28377SPZPT) £16.63. The total cost of the control circuits is estimated to be around £40. This is similar to the device suggested in [18] and [22]. Although the use of microcontroller and the control coil increases the size and cost of the system slightly compared with ‘smart stick-on’ devices in [22], the harvested power level and power density are improved significantly by the proposed method.

V. CONCLUSION

In this paper, a novel magnetic field energy harvesting method has been presented which can significantly increase the amount of the power harvested from an AC power line. To capture the magnetic field around the power line, a nano-crystalline core with a high permeability has been used. Due to the high current in the power line, the core is easily driven into the saturation operation. Very little power can be harvested when the core is saturated. To keep the core in the non-saturation operation region, a control coil has been added to the harvester. The control coil can generate a magnetic field to artificially mitigate the magnetic saturation of the core. The numerical simulation shows very good agreement with the measured results. The proposed energy harvester has achieved a power density of 2.34 $mW/cm^3/A_{rms}$, which indicates a 46.3% increment of power compared to the harvester without using the proposed method. The results have been compared with the state-of-the-art magnetic energy harvesters. The proposed method is able to harvest a high level of power and power density comparable to other reported works. The proposed harvesting method exhibits excellent potential for industrial applications such as driving power line monitoring sensors and weather stations. The proposed structure optimizes the harvested power density based on a constant primary current magnitude which is one limitation of the current work. For further research, the auto-adapting to the changing primary current will be examined to improve the performance further.

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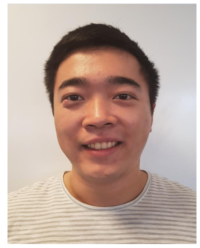

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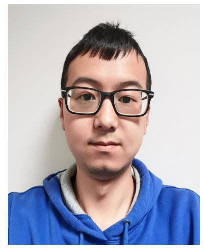

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